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# NAVAL POSTGRADUATE SCHOOL

Monterey, California



## THESIS

TEXAS INSTRUMENTS 4100 GPS  
POSITIONING SOFTWARE

by

Kevin T. Brown

September 1986

Thesis Advisor:

Muneendra Kumar

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Texas Instruments 4100 GPS  
Positioning Software

by

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Cartographer, Defense Mapping Agency  
B.A., University of North Carolina, 1982

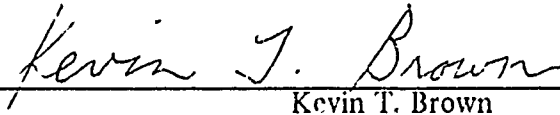
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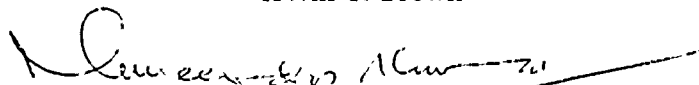
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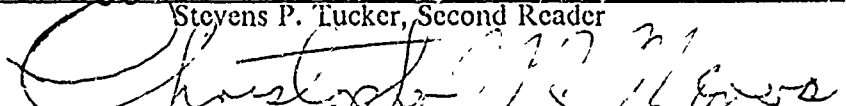
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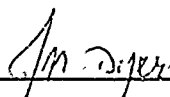
  
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## ABSTRACT

The Hydrographic Sciences Group of the Naval Postgraduate School's Department of Oceanography has a goal to establish and continue a research base related to the Global Positioning System (GPS). To meet this goal a library of programs capable of reducing GPS satellite data to position and time solutions, independent of the receiver's navigation solution, is being acquired.

This thesis describes the modification, documentation, and establishment of Texas Instruments 4100 GEOSTAR GPS software written by the Naval Surface Weapons Center for their CDC Cyber 865 computer, so that it will run on the IBM 3033 computer at NPS. Position and time solutions for either a static or dynamic receiver can be achieved using this software.

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## I. INTRODUCTION

The Hydrographic Sciences Group at the Naval Postgraduate School (NPS), conducted its first Sea Floor Benchmark Experiment in May 1985. The experiment basically was to deploy a benchmark on the ocean bottom and to establish its position with geodetic accuracy. This was to be accomplished using GPS and acoustic range data (Kumar, et al., 1984).

Beyond the goal of the Sea Floor Benchmark Experiment in May 1985 was a higher goal of establishing and continuing a GPS research base at NPS. In order to reach this goal it has become evident that a library of GPS programs should be established at NPS capable of reducing GPS data, independent of outside sources, into a format compatible for analysis.

The Texas Instruments receiver (TI-4100) was selected as one of the GPS positioning receivers to acquire data for the experiment. One version of the TI-4100 is for commercial users and the other (TI-4100 GEOSTAR) is a tri-agency version for use by the Defense Mapping Agency (DMA), National Oceanic and Atmospheric Administration (NOAA), and the United States Geological Survey (USGS). TI-4100 GEOSTAR software has been obtained for use at NPS from NOAA and the Naval Surface Weapons Center (NSWC) in Dahlgren, Virginia, for compatibility modifications with NPS's IBM 3033 mainframe computer. Of this software, three programs from NSWC, written chiefly by S. L. Meyerhoff for their CDC Cyber-865 computer, reformat GPS data and then compute receiver positions and time by either an iterative least squares approach or a Kalman filter.

The main objectives of this thesis are to describe the effort in modifying NSWC's software codes and algorithms for compatibility, and establishing them on the IBM-3033 mainframe computer at NPS. In addition, discussions of the mathematical models, results of test runs and validation of the modified software have been included. This software was acquired from NSWC for exclusive use at NPS. Future users at NPS, are encouraged to test and verify their solutions as correct before accepting them.

## II. BACKGROUND

### A. GLOBAL POSITIONING SYSTEM

GPS is a universal satellite positioning system that is independent of weather, time, or geographical position. It provides both position and time in an earth-fixed geocentric cartesian coordinate system as well as velocity data. Since it is a space based radio navigation system, it can provide accurate information to an unlimited number of users globally on or near the earth's surface. Three-dimensional position data to within a 16-m spherical error probability (SEP), velocity to within 0.06-0.15 m/s and GPS system time to within 25 ns are possible instantaneously to properly equipped users anywhere within 500 nmi of the earth (Milliken and Zoller, 1980).

The GPS is comprised of three major segments, the Space, the Control, and the User.

#### 1. *Space Segment*

The GPS when fully operational will consist of 18 active satellites (Space Vehicles or SVs) in six planes with near circular orbits at altitudes of 10,900 nmi and periods of 12 hours. Each of the six orbital planes is inclined 55 degrees to the equator and is to contain three SVs equally spaced. The configuration of the SVs in the orbital planes is such that a minimum of four SVs will be available to the user at all times, anywhere on or near the earth's surface. Each individual SV transmits its broadcast ephemeris and clock correction, plus an almanac which contains orbital parameters and clock correction estimates for all other SVs in the system.

Each SV transmits two radio frequencies simultaneously, L1 and L2 respectively, containing navigation information in the navigation data message. The L1 frequency is centered on 1575.42 MHz and the L2 frequency is centered on 1227.60 MHz. These signals are in a frequency range that provides good all weather operation and allows the user to determine ionospheric propagation delay. The L1 signal is modulated by a 10.23 MHz clock rate Precision (P) code and a 1.023 MHz Course/Acquisition (C/A) code (Spilker, 1980). The P-code is a random sequence binary code that provides the user the capability for high-precision positioning and is highly resistant to electronic and multipath interference. The C/A-code gives all users rapid acquisition capability and acts as an aid to gain access to the P-code. The

navigation data message allows the user's receiver to calculate position, velocity and GPS time by providing broadcast ephemeris, clock corrections and almanacs for all SVs. The L2 signal is modulated by the P-code only.

## *2. Control Segment*

The control segment consists of a master control station, a number of monitor stations and ground antennae located around the world. The USAF master control station is at Colorado Springs, Co., and monitor stations are located on Kwajalein Atoll, Ascension Island, Hawaii and Diego Garcia. DMA also maintains three stations in the United Kingdom, Australia and Argentina, and stations are proposed for Ecuador and Bahrain. The monitor stations acquire ranging data for each SV in a passive mode. These data are then relayed to the master control station where they are processed to determine the SV's position and signal data accuracy (Wooden, 1985). The master control station takes the relayed data, computes errors, generates a new navigation data message and then uploads this message to each SV via the ground antennae. The ground antennae transmit as well as receive satellite control information.

## *3. User Segment*

This segment consists of stationary, low, medium and high dynamic receivers designed with specific requirements for individual users. The user receivers are designed to receive and process SV data from four SVs either simultaneously or sequentially. The TI-4100 receiver determines the range from the SV by measuring the time delay of the SV's specific epoch and the user generated codes. Then making separate ranging and carrier frequency Doppler shift measurements to four SVs, the receiver calculates the user's position, clock bias error, clock drift and velocity. The position coordinates are in the World Geodetic System (WGS) 1972, an earth-fixed geocentric cartesian coordinate system.

### **B. TEXAS INSTRUMENTS 4100 NAVSTAR RECEIVER (TI-4100)**

#### *1. Characteristics and Description*

The TI-4100 receiver is portable for field operations (it is about the size of a small suitcase) but can be mounted in a standard 19-inch rack if desired. A small lightweight hand-held Control Display Unit, contains a keyboard and a display window. The receiver is modular in design and allows for easy removal and replacement of circuit boards.

The TI-4100 is a single channel dual-frequency, multiplexing NAVSTAR receiver and navigation processor that tracks up to four SVs (Texas Instruments, 1983). The dual frequency receiver allows for tracking L1 and L2 frequencies for each of the four SVs. It also has an optional dual cassette recorder for recording GPS/SV data. If GPS/SV data is to be acquired in a degraded mode (i.e. less than four SVs) there is the capability of adding an external atomic clock time standard input to the TI-4100 receiver. The TI-4100 receiver, Control Display Unit, antenna and cassette recorder are shown in Figure 2.1.

## *2. Receiver Measurements and Position Calculations*

The basic measurements made by the TI-4100 receiver are the arrival times of the SV-generated signals compared to the receiver clock, which contains a stable oscillator and a counter (Texas Instruments, 1983). Four pseudorange measurements plus the navigation data message provide enough information to calculate a three-dimensional user position solution plus the user clock correction to true GPS time. The solutions are obtained using four observation equations and four unknowns. Doppler shifts due to the relative velocity between the SV and the user are measured. Measurements are also made of the phase differences for the L1 and L2 signals between the SV and the user.

## *3. Position Accuracy*

Error statistics for the TI-4100 receiver are given in Table I. It should be noted for this table that Operating Modes using time aiding, have a positive growth rate error of 2.0 to 10.0 m/h (1-sigma) for frequency standards that allow navigation calculations to estimate precise frequency (Texas Instruments, 1983). The positioning accuracies in Table I were based on the TI-4100 receiver observing pseudoranges, Doppler shift data, phase differences for L1 and L2, then computing position, time and velocity solutions. The pseudoranges from the TI-4100 receivers are the major observables considered in this thesis.

## **C. PSEUDORANGE DATA AND THEIR CHARACTERISTICS**

The basic operation of the GPS depends on the user determining pseudorange and range rate to a number of GPS SVs which have precisely known ephemerides (Texas Instruments, 1983). Pseudorange is the apparent range, which includes the clock errors between the SV and the user's receiver. The transit time of the navigation signal between each SV and the user is measured by the receiver and then scaled by the

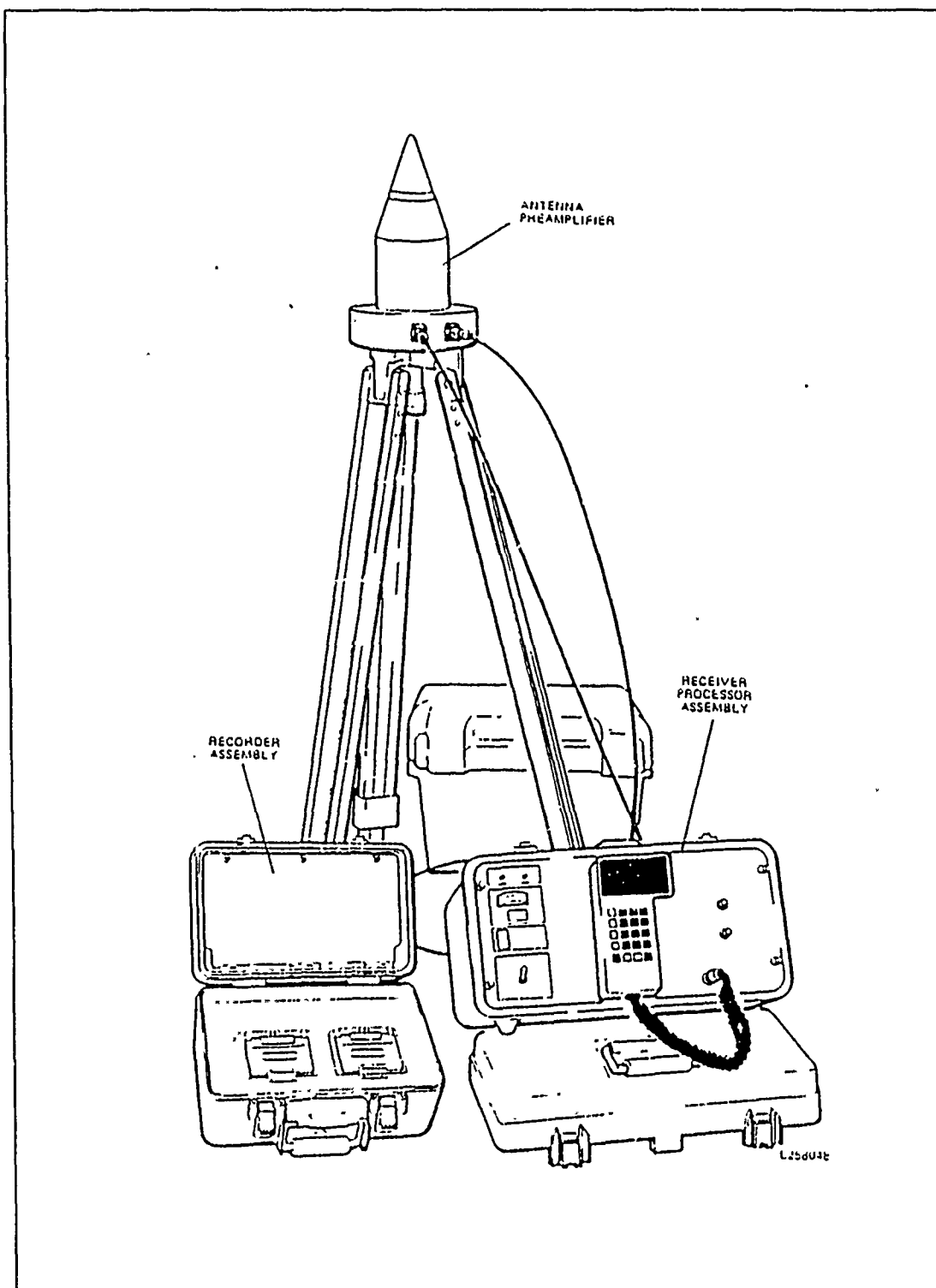


Figure 2.1 TI-4100 NAVSTAR System  
(From Texas Instruments, TI-4100 Owner's Manual, 1983).

TABLE I  
TI-4100 POSITION ACCURACY

(From Texas Instruments, TI-4100 Owner's Manual, 1983)

Operating Mode	Error Statistics	1-Sigma Position Error P (m)	1-Sigma Velocity Error C/A (m/s)	
<i>Four satellites</i>				
Stationary	3-D	13	46	N/A
0.5 g acceleration	3-D	14	47	0.15
2 g acceleration	3-D	14	47	2.00
4 g acceleration	3-D	30	55	5.00
Differential	3-D	4	12	0.15
Stationary differential	3-D	3	8	N/A
<i>Three satellites</i>				
Degraded (altitude aiding)	Horizontal	16	24	0.15
Differential degraded (altitude aiding)	Horizontal	5	6	0.15
Degraded (external cesium frequency standard time aiding)	3-D	16	47	0.15
Differential Degraded (external cesium frequency standard time aiding)	3-D	5	12	0.15
<i>Two satellites</i>				
Degraded (altitude and time aiding)	Horizontal	16	24	0.15
Differential degraded (altitude and time aiding)	Horizontal	5	6	0.15

speed of light to compute a raw pseudorange. Each raw pseudorange must be corrected for tropospheric and ionospheric propagation delays, SV clock offset, user clock bias, relativity corrections, and earth rotation corrections. The pseudorange calculation is given by Equation (2.1).

$$R_i^* = R_i + c\Delta t_{Ai} + c(\Delta t_u - \Delta t_{Si}) \quad (2.1)$$

where  $i = 1$  to 4 (pertaining to four observed SV's)



$R_i^*$  = pseudorange to the SV

$R_i$  = true range

$c$  = the speed of light

$\Delta t_{Si}$  = SV<sub>*i*</sub> clock offset from GPS system time

$\Delta t_u$  = user clock offset from GPS system time

$\Delta t_{Ai}$  = propagation delays and other errors

The tropospheric delay is estimated using simple refraction models with standard atmospheric values. Ionospheric delay is calculated by taking advantage of the dual frequency measurements of the L1 and L2 signals. The SV clock error (difference between SV clock and GPS system time) is modeled by the Control Segment and these correction coefficients are transmitted in the navigation data message from the SV to the user. User clock bias is due to the fact that the receiver clock is not perfectly synchronized to the SV clock. Relativity corrections are due to the eccentricity of the SV's orbit. Earth rotation corrections are due to the motion of the earth during the signal's propagation from SV to the user. Once four raw pseudoranges have been corrected for systematic errors, they are used to calculate the receiver's three-dimensional position and time.

The precision of position calculated by pseudoranges is dependent on the geometry of the SV's with respect to the user. This geometry is continually changing, even if the user's receiver is not in motion relative to the earth. If the intersection of the pseudoranges is orthogonal, errors in the pseudorange measurement are minimized whereas if the angle of intersection is small, errors are large because of the geometric relationship.

Geometric Dilution of Precision (GDOP) is a composite "indicator" expressing the influence of the SV's geometry on the accuracy of the user's clock offset and position determinations (Milliken and Zoller, 1980). Other terms to describe dilution of precision in position and time are: Position Dilution of Precision (PDOP) which yields dilution of precision in three-dimensions; Horizontal Dilution of Precision (HDOP) which gives dilution of precision in the two horizontal dimensions; Vertical Dilution of Precision (VDOP) which yields the dilution of precision in the vertical dimension; and finally Time Dilution of Precision (TDOP) is the dilution of precision in the user's time bias (Milliken and Zoller, 1980). GDOP, which is dimensionless, is calculated by Equation (2.2), (Milliken and Zoller, 1980),

$$GDOP = [(PDOP)^2 + (TDOP)^2]^{1/2} \quad (2.2)$$

The best geometry for a four SV configuration is the combination which results in the lowest GDOP.

Once pseudorange, Doppler shift and phase data have been acquired, and the receiver's field solutions calculated, post-processing of these data may yield improved position and time solutions. To make TI-4100 data accessible to other users with different computer processing systems, it has become necessary to format SV data in a manner that can be exchanged among independent users.

#### D. STANDARDIZED EXCHANGE FORMAT FOR NAVSTAR GPS GEODETIC DATA

This Standardized Exchange Format (SEF) was proposed by V. Dan Scott and J. Gary Peters (1983), and was adopted to make possible the universal exchange of NAVSTAR GPS data. To do this, serious compromises were made in regard to optimum magnetic tape utilization, computer execution efficiency, and computer program size (Scott and Peters, 1983). These compromises were required to allow for maximum tape compatibility between different computer systems.

##### 1. *The Basic Format*

The building block for each standardized data exchange tape is the record, which is 80 characters. Under this format, an unlabeled 9-track, ASCII-coded tape with an 80-character blocking factor is used. The header (or the first) file on a tape consists of comment records and is not considered part of the data set but is used to help the user to identify the contents of the tape. When the last data file is written on the tape a special end of information file is written (Scott and Peters, 1983).

On the tape, records fall into two categories: Control Information or Data Information records. Control Information records are used to identify which FORTRAN Format statement to use when reading data records. Data Information records consist of one of eight data items that are uniquely identified by a four digit data item number. The eight data items under the SEF are listed below:

- (1) Constant equipment and software specific data
- (2) Campaign and station specific data
- (3) Calibration data
- (4) Time tag update data
- (5) Space Vehicle specific data

- (6) Weather data
- (7) Real time solution data
- (8) Measurement data

The goal of this format is to be independent of hardware and software design. In addition to data formats, the reference Coordinate System for the data must be defined.

## 2. *Coordinate System*

The WGS 72 an earth-fixed geocentric cartesian coordinate system is defined as follows (Seppelin, 1974):

X-Axis = Intersection of the WGS 72 reference meridian plane  
and the plane of the Equator.

Y-Axis = Measured in the plane of the Equator 90 degrees  
east of the X-Axis.

Z-Axis = Parallel to the direction of the conventional  
international origin (CIO) for polar motion.

The reference ellipsoid for WGS 72 is defined by the parameters semi-major axis,  $a = 6,378,135$  m, and flattening,  $f = 1/298.26$  (Seppelin, 1974).

### III. DATA PROCESSING

The pre-processing of GPS data is carried out to obtain a format suitable for further manipulation. This is necessary when geodetic positioning of the receiver (either static or dynamic) is desired, through post-processing the SV data. Figure 3.1 portrays the flowchart for processing the TI-4100 data.

#### A. PRE-PROCESSING

##### 1. *Manipulation of Cassette Recorded Data*

The first step in processing GPS data recorded on cassettes, is to dump the raw data from the cassettes to either a 9-track magnetic tape or disk. The Applied Research Laboratories (ARL) at Austin, Texas have developed software to accomplish this fundamental task. The software at ARL can dump and process the raw data recorded on cassettes, and format the GPS data onto a 9-track magnetic tape in the SEF (Chapter II.D.). This tape can then be transferred to disk for convenience in further processing with a mainframe computer.

##### 2. *Alignment of Common Time-Tagged Data*

The alignment of common time-tagged data items is accomplished through use of the CON9TR program.

##### a. Program Description

Program CON9TR, the first of three programs acquired from NSWC (Chapter I.), reads the SEF data and formats it into another NSWC specified file. This file then becomes the input for the two remaining programs, SOLTOM and KALMN2 and has all common time-tagged data on the same record. The only calculations performed at this stage are variances on the pseudorange data and the delta range (Doppler) data which are measures of the signal to noise ratio.

The program also looks at the "quality vectors" (Texas Instruments, 1982) of the data on the 9-track SEF tape and returns an integer value representative of the data quality at that time line. Four integer values are possible:

0 = good data

1 = good data but this is the first Doppler count

14 = bad data at that point but there was not a break  
in the Doppler data

15 = bad data

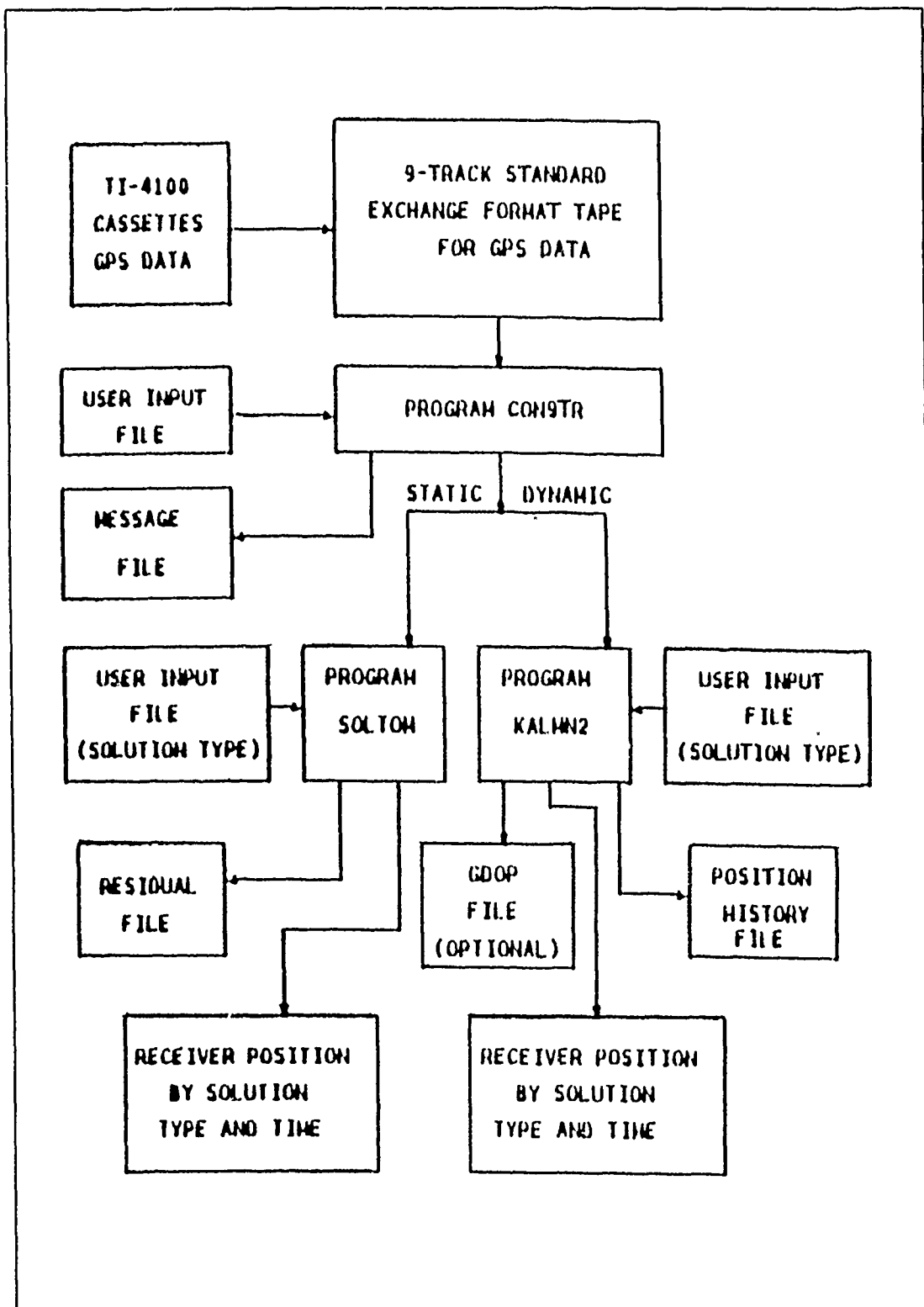


Figure 3.1 Flowchart For Processing TI-4100 GEOSTAR GPS data.

The CON9TR program requires a user input file (Figure 3.1) in addition to the GPS data in the Standardized Exchange Format during program execution. CON9TR consists of the main program and 22 subroutines. Appendix A gives a brief description of each subroutine's function and nesting.

b. Input/Output

The user input file (Figure 3.1) for the CON9TR program consists of the following:

- (1) The number of trackers, usually four but may be less than four
- (2) GPS time of the first data point to be put on the new file
- (3) Time to end data on the new file, if the end of the file is found before the time to end data, then data will end at the end of file
- (4) Range variance bias factor [ $\text{km}^2$ ]
- (5) Doppler variance bias factor [ $\text{km}^2$ ]
- (6) X-coordinate of the initial receiver position that will be put on the new files
- (7) Y-coordinate of the initial receiver position that will be put on the new files
- (8) Z-coordinate of the initial receiver position that will be put on the new files

Appendix B gives the user input guide to CON9TR program variables and format.

The first output file from CON9TR (Figure 3.1) writes all common time satellite tracking data into the same record block, and Appendix C gives the output format. The second output file writes out messages to aid the user in data quality analysis, flagging one of four quality vector conditions that exist in the data.

c. Computation of Variances

The variances for the pseudorange and Doppler data in the CON9TR program are computed by Equations (3.1) and (3.2), respectively (Texas Instruments, 1982).

$$\sigma_{\text{code}}^2 = [(B_L * N)/(10^{(C_i/10)})] * [0.5 + B_{PD}/(10^{(C_i/10)})] * K_1 + K_2 \quad (3.1)$$

where the asterisk, \*, is used to signify multiplication

$B_L$  = code loop noise bandwidth Hz

$B_{PD}$  = code loop predetection bandwidth Hz

$C_i = L_i$  carrier power to noise spectral density ratio  
dB-Hz

N = tracking mode, 1, 2, 3, 4 based on SV mode

$K_1 = (\text{chips})^2$  to  $[m^2]$  conversion:

$(29.305)^2$  for P-code

$(293.05)^2$  for C/A-code

$K_2 =$  variance bias factor  $[m^2]$

$$\sigma_{PLL}^2 = [(B_L * N)/(10^{(C_i/10)})] * \{1 + [0.5 * B_{PD}/(10^{(C_i/10)})]\} * K_3 + K_4 \quad (3.2)$$

where,

PLL = carrier phase-locked loop

$B_L$  = carrier loop bandwidth Hz

$B_{PD}$  = carrier predetection bandwidth Hz

$K_3 = [\text{rad}^2]$  to  $[m^2]$  conversion

$$= (c/2\pi f)^2$$

c = speed of light

f = L band carrier frequency

$L_1 = 1.57524 \times 10^9$  Hz

$L_2 = 1.2276 \times 10^9$  Hz

$K_4 =$  variance bias factor  $[m^2]$

#### d. Program Modifications at NPS

The original code from NSWC was written in FORTRAN IV. This code was modified at NPS to be compatible with the FORTRAN 77 compilers (FORTVS and WF77) on the IBM-3033 mainframe computer. Changes to the original code included the following,

- Changes in the formatted write statements
- Changes in variable alignments in the common statements  
(i.e. making sure double precision variables are aligned ahead of single precision variables)
- Changes in dimension size of the data arrays
- Changes in defining variables

- Changes in the placement of data initialization statements
- Addition of the Block Data subroutine to contain the moved data initialization statements and accompanying common statements.

Executive files, written at NPS to handle the input and output files for the CON9TR program, included the auto-double precision commands for all real variables using the FORTVS compiler. This modification automatically doubles the declared precision in the code and was required due to the use of 60 bit words by the CDC Cyber-865 computer and the 32 bit words by the IBM-3033 mainframe computer at NPS.

## B. DETERMINATION OF PSEUDORANGE POSITION SOLUTION

User receiver position solutions whether fixed (static) or moving (dynamic) may be calculated by post-processing the TI-4100 GEOSTAR GPS data.

### 1. *Static Positioning*

The second program, SOLTOM from NSWC (Chapter I., computes a position solution for a static receiver by using an iterative batch least squares calculation.

#### a. Program Description

Program SOLTOM computes receiver position and time, solving for initial corrections to estimates of parameters X, Y, Z, time biases and scaling factor for a tropospheric correction. Types of solution which can be selected through the user input file are described in Chapter III.B.1.c.. The program consists of the main program and 52 subroutines. Appendix D gives a brief description of each subroutine's function and nesting.

#### b. Math Models

The math models for the batch least squares solution in program SOLTOM solve for corrections to the initial estimates of the parameters desired. The observation equation is given by Equation (3.3):

$$R_i^0 = [(X_{sv} - X_p)^2 + (Y_{sv} - Y_p)^2 + (Z_{sv} - Z_p)^2]^{1/2} + CB + CD + CA + TR \quad (3.3)$$

where,

$R_i^0$  =  $i^{th}$  range observed from SV of receiver



$X_{sv}$  = earth-fixed geocentric X-coordinate of SV

$Y_{sv}$  = earth-fixed geocentric Y-coordinate of SV

$Z_{sv}$  = earth-fixed geocentric Z-coordinate of SV

$X_p$  = earth-fixed geocentric X-coordinate of receiver

$Y_p$  = earth-fixed geocentric Y-coordinate of receiver

$Z_p$  = earth-fixed geocentric Z-coordinate of receiver

CB = Clock bias term, SV or receiver depending on user input selection

CD = Clock drift term, SV or receiver depending on user input selection

CA = Clock aging term (frequency drift), SV or receiver depending on user input selection

TR = Tropospheric refraction correction.

The least squares solution of Equation (3.3) in matrix form, can be written as:

$$BP + E = 0 \quad (3.4)$$

where,

B = Matrix containing the partial derivatives of the observation equation with respect to the parameters being solved for

P = Vector containing the differences of the parameter adjusted (Pa) and the parameter estimate (Pe), (Pa - Pe)

E = Vector containing the partial derivatives of the observation equations multiplied by the weight matrix, multiplied by the data residuals

The matrix B is obtained from Equation (3.5),

$$B = A^T W A \quad (3.5)$$

where,

$A$  = Partial derivatives of data equation with respect to a parameter  $j$

$A^T$  = Transpose of the  $A$ -matrix

$w$  = Weight matrix with  $\sigma_k^2$  on the diagonal, zeros off diagonal, where  $k = 1$  to number of data points, this is the variance of noise level on a "k" range measurement

or writing Equation 3.5 in summation form,

$$B_{i,j} = \sum_{k=1}^n \partial R_k^o / \partial P_i * \partial R_k^o / \partial P_j * \sigma_k^2 \quad (3.6)$$

where,

$n$  = number of data points used in the least squares solution

$R_k^o$  =  $k^{\text{th}}$  data equation

$P_i$  =  $i^{\text{th}}$  parameter being solved for

$P_j$  =  $j^{\text{th}}$  parameter being solved for

$\sigma_k^2$  =  $k^{\text{th}}$  variance value

The  $A$ -matrix or design matrix is defined by Equation (3.7):

$$A_{i,j} = \partial R_i^o / \partial P_j \quad (3.7)$$

where,

$R_i^o$  =  $i^{\text{th}}$  data point (3.3)

$P_j$  =  $j^{\text{th}}$  parameter being solved for

The inverse of  $B$  is the variance-covariance matrix, COV, with the variances  $\sigma^2$  of the parameter corrections  $\Delta P$  that are being solved for, on the diagonal given by Equation (3.8),

$$B^{-1} = \text{COV} \quad (3.8)$$

where, COV is a 6 x 6 matrix if six parameters are being solved, or 7 x 7 if the optional 7<sup>th</sup> parameter (CA) is to be determined. The off diagonal elements are the cross-correlations of the paired parameters for that time line. The vector E in summation form is shown in Equation (3.9),

$$E_i = \sum_{k=1}^n (\partial R_k^o / \partial P_i) * \sigma_k^2 * R_{\text{res}} \quad (3.9)$$

where,

$R_k^o$  = k<sup>th</sup> data equation

n = number of data points used in least squares calculation

$P_i$  = i<sup>th</sup> parameter being solved for

$\sigma_k^2$  = k<sup>th</sup> weighted variance value

$R_{\text{res}}$  = range residuals

or writing Equation (3.9) in matrix form,

$$E = R_{\text{res}} w A \quad (3.10)$$

where,

$$\Delta P = B^{-1} E \quad (3.11)$$

and

$\Delta P$  = corrections to the initial estimates of unknown parameters being solved for (X, Y, Z, clock biases, and tropospheric refraction correction).

The following Equations (3.12) to (3.35) describe the various corrections, Time Epoch, clock, Ionospheric refraction, Tropospheric refraction, earth rotation, and relativistic effects which are required to correct pseudorange and delta range (Doppler) data (Meyerhoff, 1985).

### *Time Epoch Correction*

$$T_{sv} = tt - T_{oc} \quad (3.12)$$

where,

$T_{sv}$  = time from epoch

$tt$  = the GPS time-tag for range and delta range (Doppler)  
data

$T_{oc}$  = time of reference for clock corrections

To correct the  $T_{sv}$  for the end of the week cross over, correct  $T_{sv}$  as follows:

If  $T_{sv} < 302400$  [s] then,  $T_{sv} = T_{sv} + 604800$  [s]

If  $T_{sv} > 302400$  [s] then,  $T_{sv} = T_{sv} - 604800$  [s]

### *Clock Correction*

$$C_{cl}(tt) = [A_0 + (A_1 * T_{sv}) + (A_2 * T_{sv} * T_{sv})] * c \quad (3.13)$$

$$\Delta C_{cl}(tt) = [A_0 + (A_1 * \{(2 * T_{sv}) - td\})] * td * c \quad (3.14)$$

where,

$C_{cl}(tt)$  = clock correction for pseudorange data  
at GPS time-tag in [km]

$\Delta C_{cl}(tt)$  = clock correction for delta range  
(Doppler) data at GPS time-tag in [km]

$A_0$  = clock correction bias term [s]

$A_1$  = clock correction drift term [s/s]

$A_2$  = clock correction aging term  
[s/(s)<sup>2</sup>]

$T_{sv}$  = time from epoch

$c$  = speed of light 299792.458 [km/s]

$td$  = the Doppler count interval for delta range  
(Doppler) data

*Ionospheric Refraction Correction*

$$C_{i0}(tt) = CP_1(tt) - CP_2(tt)/(Q_1/Q_2)^2 - 1.0 \quad (3.15)$$

$$DC_{i0}(tt) = \frac{[(DOP_{L1}(tt)/Q_1) - (DOP_{L2}(tt)/Q_2)] * c}{[(Q_1/Q_2)^2 - 1.0] V_{os}} \quad (3.16)$$

where,

$C_{i0}(tt)$  = pseudorange ionospheric refraction  
delay in [km]

$tt$  = GPS time-tag for pseudorange and delta range  
(Doppler)

$CP_1$  = L1 pseudorange in [km]

$CP_2$  = L2 pseudorange in [km]

$DOP_{L1}$  = L1 Doppler count

$DOP_{L2}$  = L2 Doppler count

$DC_{i0}$  = delta range (Doppler) frequency shift due  
to ionosphere

$Q_1$  = L1 frequency multiplier (154.0)

$Q_2$  = L2 frequency multiplier (120.0)

$V_{os}$  = The nominal satellite oscillator frequency, 10.23 MHz

In Equation (3.15) the correction,  $C_{i0}(tt)$ , is used to correct the pseudorange that is time-tagged,  $tt$ . In Equation (3.16) the correction,  $DC_{i0}(tt)$ , is applied to the delta range (Doppler) data to correct it for time-tag,  $tt$ .

### *Tropospheric Refraction Correction*

The Tropospheric refraction computation can be divided into two parts, weather dependent and receiver geometry calculations (Meyerhoff, 1985).

#### *Weather Dependent Correction*

First, convert temperature to degrees Kelvin and convert humidity to a fraction:

$$T_k = T_c + 273.0 \quad (3.17)$$

$$RH = H_d/100.0 \quad (3.18)$$

where,

$T_c$  = air temperature in degrees centigrade

$H_d$  = the relative humidity in percent.

Second, compute the surface partial pressure,  $E_o$ , from temperature and relative humidity.

$$E_o = RH * 35.65 * 10 \exp[7.617 - (2285.0/T_k)] \quad (3.19)$$

Third, the components of the zenith value of tropospheric delay,  $Z_{dry}$  and  $Z_{wet}$  are calculated from,  $E_o$ , and atmospheric pressure.

$$Z_{dry} = 2.276 * P_b * 0.01 \quad (3.20)$$

$$Z_{wet} = (470 * E_o \exp(1.23/T_k) + (1.705 * 10^6 * A_h * E_o \exp(1.46/T_k^3)) \quad (3.21)$$

where,

exp = exponent

$P_b$  = the atmospheric pressure in [mb]

$A_h$  = temperature lapse rate set at 0.006 °C/m

exp = exponent It should be noted that  $Z_{dry}$  and  $Z_{wet}$  need only be recomputed, when the weather data changes.

#### *Receiver Geometry Dependent Correction*

First, to find the elevation angle,  $EV(t)$ , of the satellite at time,  $t$ , take the inverse sine of the dot product of the unit vector from the receiver to the satellite and the unit position vector of the receiver.

$$EV(t) = \sin^{-1} \frac{\vec{RS}}{MG_{rs}} \cdot \frac{\vec{R}}{MG_r} \quad (3.22)$$

where,

$\vec{RS}$  = vector from the receiver to the satellite

$MG_{rs}$  = vector's magnitude

$\vec{R}$  = position vector of the receiver

$MG_r$  = magnitude of  $\vec{R}$

$$MG_{rs} = [(X(t) - X_r)^2 + (Y(t) - Y_r)^2 + (Z(t) - Z_r)^2]^{1/2} \quad (3.23)$$

$$MG_r = [X_r^2 + Y_r^2 + Z_r^2]^{1/2} \quad (3.24)$$

where,

$X_r, Y_r, Z_r$  = the estimate of the receiver's  
position in an earth-fixed  
geocentric coordinate system

rewriting Equation (3.23),  $EV(t)$  can be written as,

$$\begin{aligned} SEV(t) = & \{[(X(t) - X_r) * X_r] \\ & + [(Y(t) - Y_r) * Y_r] \\ & + [(Z(t) - Z_r) * Z_r] / (MG_{rs} * MG_r) \end{aligned} \quad (3.25)$$

where,

$X(t), Y(t), Z(t)$  = the position coordinates in a earth-

fixed geocentric coordinate system

or

$$EV(t) = \sin^{-1} [SEV(t)] \quad (3.26)$$

Second, the multiplication factors for dry and wet as a function of elevation are calculated from the elevation angle, EV, at GPS time-tag (tt).

$$F_{dry}(t) = 1 / [\sin EV(t)] + \{0.00143 / [(\tan EV(t)) + 0.0445]\} \quad (3.27)$$

$$F_{wet}(t) = 1 / [\sin EV(t)] + \{0.00035 / [(\tan EV(t)) + 0.17]\} \quad (3.28)$$

Third,  $F_{dry}(t - td)$  and  $F_{wet}(t - td)$  are calculated in a similar manner as Equations (3.27 and 3.28).

#### *Total Tropospheric Refraction Correction*

$$TR(tt) = [Z_{dry} * F_{dry}(t)] + [Z_{wet} * F_{wet}(t)] \quad (3.29)$$

$$DTR(tt) = \{Z_{dry} * [F_{dry}(t) - F_{dry}(t - td)]\} + \{Z_{wet} * [F_{wet}(t) - F_{wet}(t - td)]\} \quad (3.30)$$

where,

$TR(tt)$  and  $DTR(tt)$  are range corrections are in [km].

#### *Earth Rotation Correction*

An earth rotation correction is required due to the rotation of the earth during the signal propagation.

$$C_{er} = [(Y(t) * X_r) - (X(t) * Y_r)] * RRE/c \quad (3.31)$$



$$DC_{er} = [(\{Y(t) - Y(t - td)\} * X_r) - (\{X(t) - X(t - td)\} * Y_r)] * RRE/c \quad (3.32)$$

where,

$X(t), Y(t), Z(t)$  = position coordinates in an earth-fixed geocentric cartesian coordinate system at pseudorange transmit time "t" used with data time tagged "tt"

$X_r, Y_r$  = estimate of the X and Y coordinate in an earth-fixed geocentric cartesian coordinate system

$RRE$  = Rotational rate of the Earth corrected for motion of the equinox  
(0.00007292115855 [rads/s])

$td$  = Doppler count interval for delta range (Doppler) data.

#### *Relativistic Correction*

The correction for the relativistic effects is due to the eccentricity of the satellite's orbit.

$$Rel(tt) = (2 * [GM]^{1/2}/c) * e * A * \sin [Ek(t)] \quad (3.33)$$

at the beginning of the Doppler count,

$$DRel(tt) = (2 * [GM]^{1/2}/c) * e * A * \sin [Ek(t - td)] \quad (3.34)$$

which yields,

$$DRC(tt) = RC(t) - RC(t - td) \quad (3.35)$$

where,

$tt$  = GPS time-tag for both pseudorange and delta range (Doppler) data

td = Doppler count interval for delta range (Doppler)  
data

t = GPS time-tag at transmission time for data time-  
tagged tt

e = eccentricity of the satellite orbit

A = the square root of the semi-major axis of the  
satellite's orbit

Ek(t) = eccentric anomaly for the satellite at pseudorange  
transmission time t

Ek(t - td) = eccentric anomaly for the satellite at the  
beginning of the Doppler count interval

GM = WGS 72 value of the Earth's gravitational constant including  
atmosphere  $398600.8 \text{ km}^3/\text{s}^2$

RC = computed range

these are the defined constants and variables.

#### c. Input/Output

There are two input files for the Soltom program (Figure 3.1). The first file is the user input file, where the user sets which types of solutions will be calculated and which data solutions will be printed out. The user input guide for this file is described in Appendix E. The second input file for SOLTOM is an output file from the CON9TR program containing records that are aligned with common time-tagged GPS data items.

There are also two output files for SOLTOM (Figure 3.1). The first file is the updated receiver position, time and other print options such as solution sigmas and clock bias terms, (as determined by the user input file). The second output file is a data corrections residual file, which can be used in plotting routines and for input to other software that handle multiple station positioning (Meyerhoff, 1986).

#### d. Program Modifications at NPS

The source code from NSWC for the SOLTOM program was written in FORTRAN IV which has been modified to run at NPS on the IBM-3033 mainframe computer.

Similar changes to the source code in the CON9TR program were also made to the SOLTOM program including the executive files (Chapter III.A.2.). The original code was written to be able to handle the precise ephemeris data as well as the onboard broadcast ephemeris data in the navigation data message from the SV. The test data for SOLTOM was generated at NSWC using the Broadcast ephemeris only, and as such, the modified program version at NPS has the Precise Ephemeris subroutines and corresponding, call, statements commented out.

#### e. Solution Techniques Through Least Squares

There are ten types of solutions possible with the SOLTOM program which are dependent on the user input file (Meyerhoff, 1985). Appendix E gives the details for the type of solution desired. Of these ten types, nine are batch least squares solutions and one solution type five is a Newton-Raphson solution (a geometrical solution, not a least squares fit). The type-five solution can be used for either static or dynamic positioning performing an independent solution at each time line. The nine batch least squares solution types fall into three data classes, Range (pseudorange), Range Difference (delta range Doppler), and Bias Range.

The reader is *WARNED*, that the Bias Range (solution type ten) has still not been tested by NSWC, and thus it should not be used at NPS. Solution types one, four, six, and nine are Range (pseudorange) solutions. Solution types two and seven are Range Difference (Doppler) solutions. Finally, solution types three and eight are combination solutions of the Range (pseudorange) and Range Difference (Doppler) data.

The SOLTOM program has the capability to run more than one iteration of batch least squares, if needed (e.g. for bad initial receiver position or time bias problems). The user has control via the user input file to set how often the least squares solution will be calculated and printed out. When a solution is to be computed, the program takes the B-matrix containing the partial derivatives of data equations with respect to the parameters being solved for, and multiplies by the variances of the range measurements (Equations 3.5 and 3.6), inverts the B-matrix, which is the variance-covariance matrix with variances of the corrections  $\Delta P$  on the diagonal, and computes the corrections to the initial estimates of the parameters being sought,  $\Delta P$  (Equation 3.11). Then Equation (3.36) gives the updated station position coordinates, clock bias, drift, aging, and Tropospheric refraction correction:

$$X = X + \Delta P_x \quad (3.36)$$

$$Y = Y + \Delta P_y$$

$$Z = Z + \Delta P_z$$

$$A_o = A_o + \Delta P_{A_o}$$

$$A_1 t = A_1 t + \Delta P_{A_1 t}$$

$$A_2 t^2 = A_2 t^2 + \Delta P_{A_2 t}$$

$$TR = TR + \Delta P_{TR}$$

where,

X, Y, Z = updated earth-fixed geocentric cartesian  
coordinates through batch least squares

$A_o$  = clock correction bias term in [s]

$A_1$  = clock correction drift term in [s/s]

$A_2$  = clock correction aging term in  
[s/(s)<sup>2</sup>]  
(optional 7th parameter to solve for)

TR = tropospheric refraction correction

The new solution takes all previous solutions and averages up to the current time line, before producing the iterated solution.

## 2. *Dynamic Positioning*

The third program, KALMN2 from NSWCC computes a position solution for a moving (dynamic) receiver, using the UDU' factorization of an eight-state extended Kalman filter (Chapter I.).

### a. Program Description

Program KALMN2 uses the first four-states for receiver position (X, Y, Z) and receiver clock bias, and the other four-states for receiver velocity along three axes (X, Y, Z) and receiver clock drift. By using the Doppler phase (change in range) measurements to smooth the pseudoranges, signal multipath and measurement noise effects can be suppressed significantly to produce a viable solution (Meyerhoff and Evans, 1986).

Note: The four-states of the velocity and clock drift are still under testing at NSWC.

The KALMN2 program consists of the main program and 43 subroutines. Appendix F, gives a brief description of each subroutine's function and nesting.

#### b. Math Models

The math model for the UDU' factorization of the inverse of the B-matrix (which contains the partial derivatives of the observation equations with respect to the parameters being solved for) used in program KALMN2 is described in Bierman (1977) and Meyerhoff (1986).

The TI-4100 receiver provides two pseudorange and two Doppler measurements (via L1 and L2 frequencies), for as many as four satellites simultaneously. The following Equations (3.37 to 3.42) describe the various corrections and conversions; receiver clock bias, continuous count (Doppler) to interval (Doppler) data, and Ionospheric refraction, which are required for the Doppler and the pseudorange data (for the Ionospheric correction) (Meyerhoff, 1985):

##### *Receiver Clock Bias Correction*

$$tt = ttr - RCB \quad (3.37)$$

where,

ttr = receiver clocks GPS time-tag for range and delta  
range (Doppler) data

tt = GPS time-tag corrected for receiver clock bias

RCB = estimate of the receiver clock bias which is  
initially set to zero and an improved estimate  
of "RCB" is made after each time line

The time delay data are multiplied by the speed of light "c" and converted to a pseudorange in [km].

##### *Continuous Count to Interval (Doppler) Data Conversion*

$$DOP_{L1}(tt)_i = DC_1(tt)_i - DC_1(tt - td)_i - (td * OFFSET1) \quad (3.38)$$

$$DOP_{L2}(tt)_i = DC_2(tt)_i - DC_2(tt - td)_i - (td * OFFSET_2) \quad (3.39)$$

where,

$td$  = Doppler count interval for delta range (Doppler) data

$DC_1(tt - td)$  ,  $DC_2(tt - td)$  = L1 and L2 continuous  
Doppler count data at the delta range interval

$DC_1(tt)$  ,  $DC_2(tt)$  = L1 and L2 continuous count Doppler  
data at the end of the delta range interval

$OFFSET_1$  ,  $OFFSET_2$  = Doppler offsets used by the receiver  
for L1 and L2, -6000 and +7600 respectively

$DOP_{L1}(tt)$  ,  $DOP_{L2}(tt)$  = L1 and L2 interval Doppler data  
for time-tag "tt"

$i$  = satellite from which data originates

The delta range (Doppler) data is obtained by converting the L1 interval Doppler data for each satellite.

$$RD(tt)_i = (-DOP_{L1}(tt)_i / V_{os} * Q_1) * c \quad (3.40)$$

where,

$V_{os}$  = nominal satellite oscillator frequency, 10.23 MHz

$Q_1$  = L1 frequency multiplier (154)

$RD(tt)$  = delta range (Doppler) for one satellite in [km]

#### *Ionospheric Refraction Correction*

$$RCI(tt)_i = CPI(tt)_i + CIO(tt)_i \quad (3.41)$$

$$RDCI(tt)_i = RD(tt)_i - DCIO(tt)_i \quad (3.42)$$

where,

CPI = uncorrected pseudorange measurement in [km]

RD(tt) = uncorrected delta (Doppler) range measurement

CIO(tt) = ionospheric refraction correction in [km]  
for pseudorange data (refer to Equation 3.15)

DCIO(tt) = ionospheric refraction corrections in [km]  
for delta (Doppler) range data (refer to Equation  
3.16).

#### *Smoothing For Noise*

The pseudorange data are contaminated due to signal multipath and other noise sources (Meyerhoff and Evans, 1986). To suppress the noise due to multipath in the pseudorange data, they are smoothed by the delta range (Doppler) data. The next set of Equations (3.43, 3.44, and 3.45) describes this smoothing:

$$B_N(tt) = R(tt) - DR(tt,ttfst) \quad (3.43)$$

$$B_{avg}(tt) = \sum B_j(tt)/N \quad (3.44)$$

$$R_{sm}(tt) = B_{avg}(tt) + DR(tt,ttfst) \quad (3.45)$$

where,

tt = GPS time-tag for pseudorange and delta range (Doppler) data

ttfst = GPS time-tag for the first good pseudorange and  
Doppler count of this data span

R(tt) = Ionospheric corrected pseudorange in [km]

DR(tt,ttfst) = Ionospheric corrected delta range (Doppler) data

N = number of data points in the span

$B_N$  =  $N^{th}$  estimate of pseudorange at time "ttfst"

$B_{avg}$  = average value of the first pseudorange

$R_{sm}(tt)$  = smooth pseudorange, if the absolute value of the difference between the raw pseudorange and smoothed pseudorange exceeds 20 [m], the data point is considered bad.

Both the pseudorange and delta range (Doppler) data must be corrected for Time Epoch, clock errors, earth rotation, relativistic effects, and Tropospheric refraction. These formulae are the same ones used for the iterative least squares solution in the SOLTOM program (Equations 3.12, 3.13, 3.14, 3.31, 3.32, 3.33, 3.34, 3.35, 3.29, 3.30). The corrected pseudorange is given by,

$$RC(tt)_i = R_{sm}(tt)_i + C_{cl}(tt)_i - Rel(tt)_i - [TR(tt)_i * (1 + CR)] + C_{er} \quad (3.46)$$

RDC(tt) is calculated in a similar manner as (3.46) for the delta range (Doppler) data.

The following Equations (3.47 to 3.51) describe computed ranges and residuals for pseudorange and delta range (Doppler) data (Meyerhoff, 1985):

#### *Computed Ranges*

$$CR(tt)_i = [(X(t)_i - X_r)^2 + (Y(t)_i - Y_r)^2 + (Z(t)_i - Z_r)^2]^{1/2} \quad (3.47)$$

for the range at the beginning of the Doppler interval,

$$CR(tt - td)_i = \{[X(t_2)_i - [X_r - (X_{Vr} * td)]]^2 + [Y(t_2)_i - [Y_r - (Y_{Vr} * td)]]^2 + [Z(t_2)_i - [Z_r - (Z_{Vr} * td)]]^2\}^{1/2} \quad (3.48)$$

where,

$X(t)$ ,  $Y(t)$ ,  $Z(t)$  = position of  $i^{th}$  satellite in an earth-fixed geocentric cartesian coordinate system at transit time  $t$

$X_r$ ,  $Y_r$ ,  $Z_r$  = estimate of the receiver's position in an earth-fixed geocentric cartesian coordinate system



$X(t_2), Y(t_2), Z(t_2)$  = position of  $i^{\text{th}}$  satellite in an  
earth-fixed geocentric  
cartesian coordinate system at  
time  $t_2$

$XV_r, YV_r, ZV_r$  = estimate of receiver's velocity

$tt$  = GPS time-tag corrected for receiver clock bias

$td$  = Doppler count interval for delta range (Doppler)  
data

Therefore the computed range difference for the individual satellites is,

$$CRD(tt)_i = CR(tt)_i - CR(tt - td)_i \quad (3.49)$$

#### *Residuals*

The pseudorange residuals are given by,

$$Romc(tt)_i = RC(tt)_i - CR(tt)_i - RCB \quad (3.50)$$

and for the delta range (Doppler) data,

$$RDomc(tt)_i = RDC(tt)_i - CRD(tt)_i - RCD \quad (3.51)$$

where,

$RC(tt)_i$  = corrected pseudorange (Equation 3.46)

$RDC(tt)_i$  = corrected delta range (Doppler)

$CR(tt)_i$  = computed pseudorange

$DCR(tt)_i$  = computed delta range (Doppler)

$RCB$  = estimate of the receiver clock bias

$RCD$  = estimate of frequency bias of the receiver oscillator  
which is also receiver clock drift.

tt = GPS time-tag corrected for receiver clock bias

td = Doppler count interval for delta range (Doppler)  
data

i = i<sup>th</sup> satellite being tracked

A state vector SP is corrected and improved over time, is composed of the receiver position in an earth-fixed geocentric cartesian coordinate system (Xr, Yr, Zr) and receiver clock bias (RCB). The last set of Equations (3.52 to 3.58) describes the observation equation and development of the state vector for the pseudorange data (Meyerhoff, 1985):

*Observation Equation*

$$D(tt)_i = CR(tt)_i + RCB \quad (3.52)$$

or rewriting it as,

$$D(tt)_i = [(X(t)_i - X_r)^2 + (Y(t)_i - Y_r)^2 + (Z(t)_i - Z_r)^2]^{1/2} + RCB \quad (3.53)$$

The H-matrix is defined as containing the partial derivatives of the observation equation with respect to the state vector:

$$\begin{aligned} H_{1,i} &= \partial D(tt)/\partial X_r = -(X(t)_i - X_r)/CR(tt)_i \\ H_{2,i} &= \partial D(tt)/\partial Y_r = -(Y(t)_i - Y_r)/CR(tt)_i \\ H_{3,i} &= \partial D(tt)/\partial Z_r = -(Z(t)_i - Z_r)/CR(tt)_i \\ H_{4,i} &= \partial D(tt)/\partial RCB = 1 \end{aligned} \quad (3.54)$$

The PA-matrix is defined as a 4x4 variance-covariance matrix for position and receiver clock bias, with off diagonal elements zeroed out and the diagonal elements set to the initial variance of Xr, Yr, Zr, and RCB. The Kalman vector K is given by the matrix equation,

$$K(tt)_i = PA(tt-) * H_i^T * [H_i * PA(tt-) * H_i^T + R_i]^{-1} \quad (3.55)$$

where,

PA(tt-) = variance-covariance matrix at time tt before it is  
updated for this data point

R = variance on the pseudorange observation

i = i<sup>th</sup> satellite being tracked

Once the PA-matrix is updated it is defined by,

$$PA(tt+) = PA(tt-) - K(tt)_i * H_i * PA(tt-) \quad (3.56)$$

#### *State Vector*

The final two equations define the updated state vector SP(tt+):

$$SP(tt+) = SP(tt-) + K(tt)_i * Romc(tt)_i \quad (3.57)$$

or

$$\begin{aligned} Xr(+) &= Xr(-) + K_1(tt)_i * Romc(tt)_i \\ Yr(+) &= Yr(-) + K_2(tt)_i * Romc(tt)_i \\ Zr(+) &= Zr(-) + K_3(tt)_i * Romc(tt)_i \\ RCB(+) &= RCB(-) + K_4(tt)_i * Romc(tt)_i \end{aligned} \quad (3.58)$$

where (+) means the updated state vector and (-) means before the updated state vector.

#### *c. Input/Output*

There are two input files for the KALMN2 program (Figure 3.1). The first file is an output file from the CON9TR program which contains records that are aligned with common time-tagged GPS data items. The second file is a user input file which sets the types of solutions and/or constraints on that solution, along with which data solutions will be printed out. The user input guide for this file is in (Appendix G).

There are three possible output files for KALMN2 (Figure 3.1). The first file is the updated receiver position and time and any other print options that are set by the user input file. The second file is a position history file that is used in printing out the updated receiver position and time file. The third file is an optional GDOP file, that can be set in the user input file.

#### d. Program Modifications at NPS

The source code from NSWEC for the KALMN2 program was written in FORTRAN IV which has been modified to run at NPS on the IBM-3033 mainframe computer. Similar changes to the source code for the CON9TR and SOLTOM program were also made to the KALMN2 program including the executive files (Chapter III.A.2.). The original code was written to handle both the precise as well as the onboard broadcast ephemeris data in the navigation data message from the SV. The test data for KALMN2 was generated at NSWEC using the broadcast ephemeris only, and as such, the modified program version at NPS has the precise ephemeris subroutines and corresponding, call, statements commented out.

#### e. Solution Techniques Through Kalman Filter

Using a UDU' factorization of an eight-state extended Kalman filter (with smoothed pseudorange measurements) in program KALMN2, there are nine types of solutions that may be calculated depending on the user input file (Appendix G).

Note that, as was stated previously in Chapter III.B.2.a., the velocity solutions from the four-velocity states are still being tested at NSWEC.

The initial receiver position (X, Y, Z) and clock biases are updated using the corrected state vector from the Kalman filter (Equations 3.57 and 3.58). If for a given time line the absolute value for the ionospheric correction CIO(tt) exceeds 20 m, that data is considered bad and flagged as such, with a quality vector set to 15. Height constrained (especially in marine areas) allows the user's receiver to track four satellites with poor GDOP and still be able to produce a good solution.

#### IV. TEST RUN RESULTS AND VALIDATION

The testing of the three programs CON9TR, SOLTOM, KALMN2 was accomplished by using two independent data sets in the SEF on 9-track magnetic tape as received from NSW. Included also were hardcopy printouts, listing the solutions from those data sets using the CON9TR, SOLTOM, and KALMN2 programs on NSW's CDC Cyber-865 computer. A direct comparison of the output listing files containing the receiver position solutions and times for the SOLTOM and KALMN2 programs from both the NSW's CDC Cyber-865 and the NPS IBM-3033 computers could then be made.

After the original source codes and some algorithms were modified for compatibility on the NPS IBM-3033, the programs were test run, using the FORTVS compiler with an auto-double precision option discussed previously (Chapter III.A.2.).

##### A. STATIC POSITION SOLUTION RESULTS

Table II shows the differences between results computed at NPS and NSW using the NSW test data set (from Henderson Point, 85006) for the SOLTOM program. Running the CON9TR and SOLTOM programs, position solution results (X, Y, Z) were duplicated to the millimeter level for solution type seven; to the centimeter level for solution types one and two; to the decimeter level for solution types four and six; and to the meter level for solution type nine (Appendix E).

The above differences in the SOLTOM solutions are considered insignificant due to the limitations of the observed data (Meyerhoff, 1986).

##### B. DYNAMIC POSITION SOLUTION RESULTS

Table III shows the differences between results (beginning and ending solutions using the test data set) computed at NPS and NSW using the NSW test data (from Henderson Point, 95005) for the KALMN2 program. Running the CON9TR and KALMN2 programs, position solutions and clock biases were duplicated to the millimeter and  $10^{-6}$  second level respectively.

It should be noted that not all options (Chapter III.B.2 and Appendix G) within the programs have been checked and tested. At this point it can be said that these programs have been established and validated on the IBM-3033 at NPS to the degree of being able duplicate NSW's results if the same user options are followed.

TABLE II  
CON9TR AND SOLTOM SOLUTION RESULTS

*Difference Between NPS and NSWC Solutions*

Solution Type	X,Y,Z Position (kilometers)	Clock Bias (seconds)	Clock Drift (seconds)	Number Of Data Points
<i>ONE</i> Range Data Receiver Clock	$10^{-5}$	$10^{-9}$	$10^{-11}$	1133
<i>TWO</i> Doppler Data Receiver Clock	$10^{-5}$	N/A	$10^{-11}$	1125
<i>FOUR</i> Common Range Receiver Clock	$10^{-4}$	N/A	N/A	832
<i>SIX</i> Range Data SV Clock	$10^{-4}$	$10^{-7}$	$10^{-12}$	1133
<i>SEVEN</i> Doppler Data SV Clock	$10^{-7}$	N/A	$10^{-11}$	1125
<i>NINE</i> Common Range SV Clock	$10^{-3}$	$10^{-6}$	$10^{-12}$	832

TABLE III  
CON9TR AND KALMN2 SOLUTION RESULTS

GPS Time-Tag (seconds)	<i>Difference Between NPS and NSWC Solutions</i>		
	(X,Y,Z) (kilometers)	Clock Bias (seconds)	Number of Doppler Edited Points
<i>First Solution</i>			
14129.00	$10^{-5}$	$10^{-9}$	N/A
<i>Last Solution</i>			
17499.00	$10^{-5}$	$10^{-6}$	9

## V. SUMMARY

How to process the GPS satellite data from raw cassettes off the TI-4100 GEOSTAR receiver to a reduced position and time solution has been discussed.

The capability of processing raw data from cassettes to SEF at NPS is a task for the future.

NPS at this time has the capability, starting with a SEF 9-track magnetic tape, to use the CON9TR program (where the common time-tagged data are aligned), to select either the SOLTOM (an iterative least squares for positioning a static receiver) or the KALMN2 program (which uses a Kalman filter for positioning a dynamic receiver) and to compute position and time solutions. The calculations for program CON9TR, and the math models for programs SOLTOM and KALMN2 were documented. The changes required to modify the original codes and algorithms for these programs written for NSWC's CDC Cyber-865 computer to make them compatible with the IBM-3033 computer at NPS have been described. Testing of the programs shows a successful conversion (with the restrictions discussed in Chapter IV.) of the programs to the IBM-3033 mainframe computer. This software forms a basis for a GPS programs library that will aid research using the GPS at NPS.



## VI. RECOMMENDATIONS

Since the conversion of the CON9TR, SOLTOM, and KALMN2 programs has been successfully tested using the two independent data sets from NSWC, it is recommended to explore other options within the programs set by the user input files for the SOLTOM and KALMN2 programs. Options that should be explored for the SOLTOM program include the use of the precise ephemeris and clock files, the use of more than one iteration for the solutions, and the calculation of Newton-Raphson range solutions followed by a comparison with the iterative batch least squares solutions for a given time line. The KALMN2 program should be explored by using the precise ephemeris and clock files, turning the height constraint on and off in the user input file and comparing the solution results. The refraction correction should be turned on and off to see how the solutions are affected (this is another option in the user input file).

It is further recommended to explore the possibilities of rewriting or adding codes and algorithms to improve the solution corrections for updating the four-state vectors of the velocity in the extended eight-state Kalman filter making them reliable for use in velocity solutions.

In the future TI-4100 software for carrier phase data, differential positioning etc., should be acquired and modified to be compatible with the IBM-3033 computer at NPS.

## APPENDIX A

### CON9TR SUBROUTINE DESCRIPTIONS AND NESTING

INPUT -	This routine reads the user inputs.
GETDAT -	This routine reads the next set of satellite tracking data from the 9-track Standard tape and also updates weather, Navigation data, almanac and calibration.
RDDTL -	This routine initializes the quality vector flags and controls branching of the program depending on a particular error flag.
ER9TR -	This routine controls branching of the program for several error and terminating conditions.
UDNTDT -	This routine processes non-tracking data so that it can be used, after it determines which type of non-tracking data was read from the 9-track Standard tape.
PRTSL -	This routine prints tape solutions.
UDWTD -	This routine gets the weather data from the 9-track Standard tape and stores it in common that will be used to calculate the tropospheric correction.
UDSATD -	This routine reads the 9-track Standard tape and defines new satellite orbit clock parameters.
FDTRN -	This routine will give the tracker number for the satellite that the new data is for.
DEDPOF -	This routine stores the values for the L1 and L2 Doppler offsets so that they may be used in the program.
PRTPDT -	This routine prints any unused 9-track Standard tape data.
UDTRD -	This routine decides if the tracking data is continuous count Doppler range or data quality measurement blocks and then calls the correct subroutine to handle the correct data type.
DEQUDT -	This routine defines data quality and then stores the data quality information. The satellite tracker mode and the quality vectors are used to determine if the data are good. The remaining data values in this block are used to calculate errors on the tracking data.
DERGDT -	This routine stores the range data and the signal to noise data in correct data array that will be processed.
DEDPDT -	This routine converts the accumulated Doppler phase data into range difference data. The Doppler phase data is corrected for offset and then it is differenced with preceding data if the preceding data was good.

- GNINP - This routine reads the logical unit number of the input file and returns the information read one item at a time.
- GNID - This routine controls how data items are read by reading a four digit data type number.
- IN9TR - This routine initializes the read package of the 9-track Standard tape and sets up a data block for the data items read off of the tape.
- BLDATA - This routine contains the data that has been read off of the 9-track Standard tape.
- SDAT - This routine takes the site name and the data interval from the 9-track Standard tape read common and passes these values.
- FSIG - This routine determines the difference between the raw range and the range difference data for the satellite being tracked.
- BLOCK DATA - This routine was added at NPS to make this program compatible with the FORTRAN 77 compilers on the IBM-3033 mainframe computer. It consists of common statements and data statements that the rigorous compilers at NPS would not permit where they were placed in the original source code of CON9TR.

```

MAIN PROGRAM CON9TR
  INPUT
  GETDAT
    RDDTL
      ER9TR
        UDNTDT
          PRTSL
            UDWTDT
              UDSATD
                FDTRN
                  DEDPOF
                    PRTPDT
                      UDTRD
                        DEQUDT
                          FDTRN
                            DERGDT
                              FDTRN
                                DEDPDT
                                  FDTRN
                                    GNINP
                                      GNID
                                        IN9TR
                                          BLDATA
                                            GNINP
                                              RDDTL
                                                SDAT
                                                  FSIG
                                                    BLOCK DATA

```

## APPENDIX B

### INPUT GUIDE FOR PROGRAM CON9TR

( by S. L. Meyerhoff, NSWC)

This is the user input file for the program with variable names and descriptions. The input is format free.

*line 1*

- |         |   |   |
|---------|---|---|
| 1: NSAT | = | number of trackers (4)  |
| 2: TSS  | = | GPS time of first data point to put on new file                                 |
| 3: TES  | = | time to end data on new file, if EOF found before TES then data will end at EOF |
| 4: K2   | = | range variance bias factor (kilometer) <sup>2</sup>                             |
| 5: K4   | = | doppler variance bias factor (kilometer) <sup>2</sup>                           |

*line 2*

- |      |   |   |
|------|---|---|
| 1: X | = | X coordinate of initial receiver position that will be put on the new files |
| 2: Y | = | Y coordinate of initial receiver position that will be put on the new files |
| 3: Z | = | Z coordinate of initial receiver position that will be put on the new files |

## APPENDIX C

### TEXAS INSTRUMENTS GPS SATELLITE RECEIVER FILE FORMAT

( by S. L. Meyerhoff, 1984, NSWC )

Data from the DMA version of the TI-4100 GPS satellite receiver can be put into the following format. In this format all common time satellite tracking data will be in the same record block. The format for this file is as follows.

var	type	meaning
<i>Record One</i>		
word 1 ITYPE	intg	This is the data type for the next record
<i>Record Two</i>		
If ITYPE equals one then record two will contain initial information.		
word 1 RL1OFF	real	frequency bias offset for L1
word 2 RL2OFF	real	frequency bias offset for L2
word 3 PB	real	pressure in (millibars)
word 4 TP	real	temperature (degrees Celsius)
word 5 HD	real	relative humidity (percent)
word 6 X	real	X coordinate of initial receiver position (kilometers)
word 7 Y	real	Y coordinate of initial receiver position (kilometers)
word 8 Z	real	Z coordinate of initial receiver position (kilometers)
word 9 NTR	intg	maximum number of trackers used will be 4 or larger
word 10 DTREC	real	user given data interval (seconds)
word 11 SITE(1)	char	site identification for data
word 12 SITE(2)	char	site identification for data

(continued)

If ITYPE equals two then record two will contain satellite ephemeris data (navigation data message)

word 1 J	intg	tracker number
word 2 ISAT(J)	intg	satellite prn number
word 3 AS(1)	real	satellite clock bias in seconds
word 4 AS(2)	real	satellite clock drift (seconds/second)
word 5 AS(3)	real	satellite clock aging (seconds/second*second)
word 6 CICS	real	cross track cosine amplitude (radians)
word 7 CISS	real	cross track sine amplitude (radians)
word 8 CRCS	real	radial cosine amplitude (kilometers)
word 9 CRSS	real	radial sine amplitude (kilometers)
word 10 CUCS	real	in track cosine amplitude (radians)
word 11 CUSS	real	in track sine amplitude (radians)
word 12 DNS	real	corrections to mean motion (radians)
word 13 ES	real	eccentricity
word 14 IDOTS	real	inclination rate (radians/second)
word 15 IOS	real	inclination (radians)
word 16 MOS	real	mean anomaly (radians)
word 17 OMEDS	real	right ascension rate (radians/second)
word 18 OMEGS	real	right ascension (radians)
word 19 SQAS	real	square root of semi-major axis (kilometers)

word 20 ADE	real	age of data ephemeris (seconds)
word 21 TOCS	real	clock epoch (seconds)
word 22 TOES	real	ephemeris epoch (seconds)
word 23 IWKNOS	intg	week number
word 24 WS	real	argument of perigee (radians)
word 25 IEDATS	intg	sv health
word 26 ADC	real	age of data clock (seconds)

If ITYPE equals three then record two will contain the tracking information.

word 1	TT	real	GPS time-tag for data that follows (seconds)
word 2	ISAT(1)		The PRN number for the
to	to	intg	satellite being tracked
word NTR + 1	ISAT(NTR)		on trackers i to NTR
word NTR + 2	CR1(1)		The L1 pseudorange on
to	to	real	each tracker (seconds)
word NTR*2 + 1	CR1(NTR)		
word NTR*2 + 2	CR2(1)		The L2 pseudorange on
to	to	real	each tracker
word NTR*3 + 1	CR2(NTR)		(seconds)
word NTR*3 + 2	DOP1(1)		The L1 continuous
to	to	real	count doppler data on
word NTR*4 + 1	DOP1(NTR)		each tracker (cycles)
word NTR*4 + 2	DOP2(1)		The L2 continuous
to	to	real	count doppler data on
word NTR*5 + 1	DOP2(NTR)		each tracker (cycles)
word NTR*5 + 2	SGR1(1)		The variance on the L1
to	to	real	pseudorange
word NTR*6 + 1	SGR1(NTR)		(kilometer*kilometer)
word NTR*6 + 2	SGR2(1)		The variance on the L2

to	to	real	pseudorange
word NTR*7+1	SGR2(NTR)		(kilometer*kilometer)
word NTR*7+2	SGD1(NTR)		The variance on the L1
to	to	real	doppler
word NTR*8+1	SGD1(NTR)		(kilometer*kilometer)
word NTR*8+2	SGD2(1)		The variance on the L2
to	to	real	doppler
word NTR*9+1	SGD2(NTR)		(kilometer*kilometer)
word NTR*9+2	MQVEL(1)		The quality vector for
to	to	intg	all trackers
word NTR*10+1	MQVEL(NTR)		15 = loss of lock
			14 = bad data, no
			loss of lock
			1 = good range data
			bad doppler data
			0 = all data good



## APPENDIX D

### SOLTOM SUBROUTINE DESCRIPTIONS AND NESTING

CARDIO -	This routine reads the input for program SOLTOM from the output of CON9TR.
LLXYZ -	This routine converts position in the geodetic coordinate system to the earth-fixed geocentric coordinate system.
SIGXYZ -	This routine converts sigmas in the geodetic system into sigmas in the earth-fixed geocentric coordinate system.
MATRIX -	This routine performs matrix operations by calling routines in the IMSL library.
LINV2F -	This routine is in the IMSL and does a matrix inversion.
VMULFF -	This routine is in the IMSL and does matrix multiplication.
VMULFM -	This routine is in the IMSL and does a transpose of matrix multiplication.
INDAT -	This routine will pass initial values to some data arrays.
NEWSOL -	This routine sets up the configuration for a for a given solution routine.
LSTSOL -	This routine calculates a sequential least squares solution for the receiver position and clock.
GETDAT -	This routine reads the next set of satellite tracking data from CON9TR output file and it will also update weather, Navigation data, almanac and calibration.
DEDPDT -	This routine converts the accumulated Doppler phase data into range difference data by correcting phase for offset and then differencing it with data from before (if before data is good).
DEFBR -	This routine defines bias range
CRDAT -	This routine defines correction for receiver bias.
BSADR -	This routine will correct data for receiver clock bias, drift and also correct GPS time tag for the end of week cross over.
CRDAT2 -	This routine converts data into range residuals and corrects data for error sources.
ION -	This routine corrects for ionospheric correction.
IONRD -	This routine corrects range difference data.

EPHDATA -	This routine defines the following values from the ephemeris data, satellite tracker number, satellite bias, drift and aging terms, semi-major axis of satellite orbit, eccentricity of the satellite orbit and epoch time for clock terms.
CLOCK -	This routine adds satellite and clock error and converts it to range measurements in kilometers and also performs the same for range difference data.
SATPOS -	This routine will find the position of the satellite from the Navigation Message or from the Precise Ephemeris.
ESTPOS -	This routine finds the position of the satellite from the Precise Ephemeris data.
ZANG -	This routine finds the Zenith angle by dotting the X, Y, Z positions of the satellite receiver position vector to the vector from the receiver to the satellite.
RES -	This routine finds the residual by calculating the range to a satellite and subtracting it from the observed range. This is also performed for range difference data.
SMOT -	This routine determines an earth rotation correction.
TROP -	This routine finds tropospheric refraction correction.
REL -	This routine finds a relativistic correction to the data.
FSIG -	This routine finds the variance (sigma squared) for the raw range and range difference data for the satellite being tracked.
SOLTNS -	This routine calls the different routines to sum data in the correct part of the "B" matrix and "E" vector depending on which options have been set by the user for type of solution.
SMPT1 -	This routine calls a routine to define additions to "B" matrix and "E" vector plus directing the called routine on where to store this information for the "B" matrix and "E" vector (for range data only).
UDRRC -	Update range solution matrix receiver clocks. Then store data in matrix so that solution can be computed.
SMPT2 -	This routine calls a routine to define additions to "B" matrix and "E" vector plus directing the called routine on where to store this information for "B" matrix and "E" vector (for range difference data only)
UDRDRC -	Update range difference solution matrix receiver bias. This routine stores data in matrix so a solution can be computed.
SMPT3 -	This routine calls a routine to define additions to "B" matrix and "E" vector, plus

	directing the called routine on where to store this information for the "B" matrix and "E" vector (for range and range difference data only).
NETRAP -	This routine uses a Newton-Raphson method to calculate time bias adjustment and then improve the receiver initial position.
CROUT -	This routine calls an IMSL routine that finds the determinate of a matrix.
LINV3F -	This is an IMSL routine that calculates the determinate of a matrix.
POSAVG -	This routine finds the average of all positions up to current time line.
SMPT6 -	This routine calls a routine to define additions to "B" matrix and "E" vector plus directing the called routine on where to store this information (for range data only, satellite biases)
UDRSC -	This routine stores data in matrix so solution so solution can be computed after the range solution matrix and satellite clocks have been updated.
BELIM -	This routine eliminates certain parameters in the "B" matrix.
BMSTR -	This routine stores data in a matrix so a solution can be computed.
SMPT7 -	This routine calls a routine to define additions to the "B" matrix and "E" vector plus directing the called routine on where to store this information (for range difference data only, satellite clock).
UDRDSC -	This routine stores data in a matrix so that a solution can be computed after updating the range solution matrix and satellite bias.
SMPT8 -	This routine calls a routine to define additions to "B" matrix and "E" vector plus directing the called routine where to store this information (for range and range difference data only).
SMPT9 -	This routine calls a routine to define additions to the "B" matrix and "E" vector plus directing the called routine on where to store this information (for common time range data only).
UDCRSC -	This routine stores data in a matrix so that a solution can be computed after updating the common range solution matrix and satellite clocks.
ELIM -	This routine finds data needed for elimination and then calls a routine to do that elimination.
SMPT10 -	This routine calls a routine to define additions to the "B" matrix and "E" vector plus directing the called routine on where to store this information (for Doppler data used as bias range data).

- BSRNG - This routine defines additions to the "B" matrix and "E" vector.
- NEWITR - This routine resets data so that a new iteration can be done.
- BLOCK DATA - This routine was added at NPS to make this program compatible with the FORTRAN 77 compilers on the IBM-3033 mainframe computer system. It contains common statements and data statements that NPS's compilers would not permit where they were placed in the original code of program SOLTOM.

```

MAIN PROGRAM SOLTOM
CARDIO
LLHXYZ
SIGXYZ
MATRIX
      LINV2F
      VMULFF
      VMULFM
INDAT
NEWSOL
      LSTSOL
      MATRIX
GETDAT
      DEDPDT
      DEFBR
CRDAT
      BSADR
      CRDAT2
      ION
      IONRD
      EPIIDAT
      CLOCK
      SATPOS
      ESTPOS
      ZANG
      RES
      SMOT
      TROP
      REL
      FSIG
SOLTNS
      SMPT1
      UDRRC
      SMPT2
      UDRDRC
      SMPT3
      UDRRC
      UDRDRC
      NETRAP
      CROUT
      LINV3F
      CRDAT
      POSAVG
      SMPT6
      UDRSC
      BELIM
      MATRIX
      LINV2F
      VMULFF
      VMULFM
      BMSTR
SMPT7

```

UDRDSC  
BELIM  
BMSTR  
SMPT8 UDRSC  
UDRDSC  
SMPT9 UDCRSC  
ELIM BELIM  
BMSTR  
SMPT10 BSRNG  
CRDAT  
UDRSC  
NEWSOL  
NEWITR  
GETDAT  
BLOCK DATA

# APPENDIX E

## INPUT GUIDE AND SOLUTION TYPES FOR PROGRAM SOLTOM

( by S. L. Meyerhoff, NSWC)

### INPUT GUIDE

<i>Var</i>	<i>Type</i>	<i>Description</i>
<i>CARD ONE</i>		
		<i>Format (2F10.0,6I5)</i> (This line can be read format free)
col 1 to 10 TSS	real	The GPS time tag for data at start of solution (seconds)
col 11 to 20 TES	real	The GPS time-tag of last data point to use in solution (seconds)
col 21 to 25 (right justified) NPN	integer	The number of time lines of data needed before first solution
col 26 to 30 (right justified) NPB	integer	The number of time lines of data between solutions
col 31 to 35 (right justified) ITRY	integer	The maximum number of iterations
col 36 to 40 (right justified) NSAT	integer	The maximum number of trackers to process at once (range 1 to 4)
col 41 to 45 (right justified) IGT	integer	= 1 if data source is Standard 9-track format = 2 if data source GESAR test file format = 3 if data source is NAV IF tape
col 46 to 50 (right justified) ISP	integer	= 1 for satellite position from NAV data = 2 for satellite position from Celestial Earth fixed trajectory files
col 51 to 55 (right justified) IAGE	integer	= 1 solve for clock aging, otherwise not solved for
col 56 to 60 (right justified) ICLOCK	integer	= 0 solve clock corrections are from NAV data message = 1 clock corrections are post fit data from cards

*CARD TWO (receiver position)* *Format (1I10.7G10.0)*  
(This card can be read format free)

col 10

IFLAG	integer	= 0 for cartesian coordinates = 1 for geodetic coordinates
col 11 to 20 XLAT	real	latitude or X coordinate for position (degrees or kilometers)
col 21 to 30 YLOG	real	longitude or Y coordinate for position (degrees or kilometers)
col 31 to 40 ZHT	real	height or Z coordinate for position (kilometers)
col 41 to 50 TB	real	time bias for receiver clock (kilometers)
col 51 to 60 TD	real	time drift for receiver clock (kilometers/second)
col 61 to 70 TO	real	epoch for clock drift (given and solution) If negative, then first used time line is the epoch for the solution clock drift
col 71 to 80 AGE	real	aging for receiver clock (kilometers/second*second)
<i>CARD THREE (Reference Geoid)      Format (2G10.0)</i> (This card can be read format free)		
col 1 to 10 AG	real	semi-major axis of the reference geoid (kilometers)
col 11 to 20 ROBL	real	Obliquity of the reference geoid
<i>CARD FOUR (Sigmas for Position)      Format (7G10.0)</i> (This card can be read format free)		
col 1 to 10 SIGLT	real	sigma of X or latitude coordinate (kilometers)
col 11 to 20 SIGLG	real	sigma of Y or longitude coordinate (kilometers)
col 21 to 30 SIGHT	real	sigma of Z or height coordinate (kilometers)
col 31 to 40 SIG(1)	real	sigma of refraction scaling constant
col 41 to 50 SIG(2)	real	sigma on receiver or satellite 1 time bias (kilometers)
col 51 to 60 SIG(3)	real	sigma on receiver or satellite 1 clock drift (kilometers/second)

col 61 to 70		
SIG(4)	real	sigma for aging term or satellite 2 bias (kilometers/second*second)

*CARD FIVE (Sigmas for Position)      Format (7G10.0)*  
(This card can be read format free)

col 1 to 10		
SIG(5)	real	sigma on satellite 2 drift (kilometers/second)

col 11 to 20		
SIG(6)	real	sigma for satellite 3 bias (kilometers)

col 21 to 30		
SIG(7)	real	sigma for satellite 3 drift (kilometers/second)

col 31 to 40		
SIG(8)	real	sigma for satellite 4 bias (kilometers)

col 41 to 50		
SIG(9)	real	sigma for satellite 4 drift (kilometers)

### *SOLUTION TYPES*

*CARD SIX (Types of Solutions to do)      Format (I6I5)*  
(This card cannot be read format free)

col 5		
NSOL(1)	integer	= 1 for range solution receiver clock 0 = no

col 10		
NSOL(2)	integer	= 1 for range difference solution receiver clock = 0 no

col 15		
NSOL(3)	integer	= 1 for range and range difference solution receiver clock = 0 no

col 20		
NSOL(4)	integer	= 1 for common time range solution
	receiver clock	= 0 no

col 25		
NSOL(5)	integer	= 1 for Newton-Raphson range solution = 0 no

col 30		
NSOL(6)	integer	= 1 for range solution satellite
	clocks	= 0 no

col 35		
NSOL(7)	integer	= 1 for range difference solution
	satellite clock	= 0 no

col 40



NSOL(8)	integer	= 1 for range and range difference solution satellite clock = 0 no
col 45 NSOL(9)	integer	= 1 for common time range solution, satellite clock = 0 no
col 50 NSOL(10)	integer	= 1 for doppler data used as bias range data = 0 no
<p><i>CARD SEVEN (Variance Bias Factor)      Format (2G10.0)</i>          (This card can be read format free)</p>		
col 1 to 10 K2	real	bias factor for variance on range data
col 11 to 20 K4	real	bias factor for variance on doppler data
<p><i>CARD EIGHT (Print Options)      Format (5I5)</i>          (This card can be read format free)</p>		
col 5 IPRT(1)	integer	= 1 print position solution (X,Y,Z) = 0 do not print
col 10 IPRT(2)	integer	= 1 print solution sigmas and clock terms = 0 do not print
col 15 IPRT(3)	integer	= 1 print data and time tags = 0 do not print
col 20 IPRT(4)	integer	= 1 print residuals, range, trop, data sigma = 0 do not print
col 25 IPRT(5)	integer	= 1 print satellite position = 0 do not print
col 30 IPRT(6)	integer	= 1 print residuals and all data corrections = 0 do not print
col 35 IPRT(7)	integer	= 1 print solution position in lat, long, height = 0 do not print
col 40 IPRT(8)	integer	= 1 print real time solutions from

9-track

= 0 do not print

*CARD NINE (Weather Data, Elev. Cutoff) Format (4G10.0)*  
(This card can be read format free)

col 1 to 10		
PB	real	pressure in millibars
col 11 to 20		
TC	real	temperature in degrees Centigrade
col 21 to 30		
HD	real	relative humidity in percent
col 31 to 40		
EL	real	elevation angle cutoff (degrees)

*CARD TEN (Station Number) Format (I5)*  
(This card can be read format free)

col 1 to 5		
ISTA	integer	station identification

*CARD ELEVEN (Tracker 1 Clock Parameters) Format (3G10.0)*

col 1 to 10		
AO	real	clock bias of satellite tracked on tracker 1
col 11 to 20		
A1	real	clock drift of satellite tracked on tracker 1
col 21 to 30		
A2	real	clock aging of satellite tracked on tracker 1

*CARD TWELVE (Tracker 2 Clock Parameters) Format (3G10.0)*  
(This card can be read format free)

col 1 to 10		
AO	real	clock bias of satellite tracked on tracker 2
col 11 to 20		
A1	real	clock drift of satellite tracked on tracker 2
col 21 to 30		
A2	real	clock aging of satellite tracked on tracker 2

*CARD THIRTEEN (Tracker 3 Clock Parameters) Format (3G10.0)*  
(This card can be read format free)

col 1 to 10		
AO	real	clock bias of satellite tracked on tracker 3
col 11 to 20		
A1	real	clock drift of satellite tracked on tracker 3
col 21 to 30		
A2	real	clock aging of satellite tracked on tracker 3

*CARD FOURTEEN (Tracker 4 Clock Parameters) Format(3G10.0)*  
 (This card can be read format free)

col 1 to 10 A0	real	clock bias of satellite tracked on tracker 4
col 11 to 20 A1	real	clock drift of satellite tracked on tracker 4
col 21 to 30 A2	real	clock aging of satellite tracked on tracker 4

## APPENDIX F

### KALMN2 SUBROUTINE DESCRIPTIONS AND NESTING

CARDIO -	This routine reads input for program.
LLHXYZ -	This routine converts latitude, longitude and height to X, Y, Z in earth-fixed geocentric cartesian coordinates.
SIGXYZ -	This routine converts sigmas in the geodetic coordinate system into sigmas in the earth-fixed geocentric coordinate system.
MATRIX -	This routine performs matrix operations by calling the proper routine in the IMSL library.
LINV2F -	This routine is in the IMSL and performs a matrix inversion.
VMULFF -	This routine is in the IMSL and performs a matrix multiplication.
VMULFM -	This routine performs a transpose of multiplication of matrices.
INDAT -	This routine gives the initial values to the "B" matrix (U in Kalman filter)
TIMEUP -	This routine uses a UDU' factorization method to update state matrix.
PROMPT -	This routine aids in the UDU' factorization.
GETDAT -	This routine reads the next set of satellite tracking data from CON9TR output file.
NEWTRAN -	This routine reduces noise and multipath in the range data.
DEDPDT -	This routine converts Doppler phase into range differenced data.
DEFBR -	This routine defines bias range.
CRDAT -	This routine defines corrections for receiver bias.
BSADR -	This routine will correct data for receiver clock bias and drift and also correct GPS time-tag for the end of week cross over.
CRDAT2 -	This routine converts data into range residuals and corrects data for error sources.
ION -	This routine corrects for ionospheric refraction.
IONRD -	This routine corrects range difference data
EPHDAT -	This routine defines the values from the ephemeris data.
CLOCK -	This routine adds satellite and clock error and

converts it to range measurements in kilometers and also perform the same for range difference data.

SATPOS - This routine will find the position of the satellite from the navigation data message or from the Celestial Earth-Fixed Trajectory (Precise Ephemeris).

ESTPOS - This routine finds the position of the satellite from the Precise Ephemeris data.

ZANG - This routine finds the zenith angle by dotting the X, Y, Z positions of the satellite receiver position vector to the vector from the receiver to the satellite.

RES - This routine finds the residual for ranges.

SMOT - This routine determines an earth rotation correction.

TROP - This routine calculates a tropospheric refraction correction.

REL - This routine finds a relativistic correction to the data.

FSIG - This routine calculates the variance for raw pseudorange and range differenced data for the satellite being tracked.

GDOP - This routine if turned on, writes a GDOP file.

LINV3F - This routine is in the IMSL and performs a matrix inversion

KALFIL - This routine uses corrected data to do the Kalman filter.

INKAL - This routine sets up initial covariance matrix in UDU' format.

UDFACT - This routine puts Apriori covariance matrix into UDU' factorized matrix.

RKAL - This routine calculates partial derivatives of the data equation for pseudorange data.

UPDATE - This routine will update the Kalman solution for one data point.

DPKAL - This routine calculates partial derivatives of the data equation for delta (Doppler) range differences.

CONSTR - This routine will constrain the solution to the surface of a sphere (height) and constrain velocity.

XYZLLH - Converts X, Y, Z in an earth-fixed geocentric coordinate system to geodetic coordinate system.

PRNSOL - This routine prints solutions.

COVEVL - This routine finds the covariance matrix from the UDU' factorized matrix in U.

BLOCK DATA - This routine was added at NPS to handle

data statements and common statements that  
had to be moved in the code or written, to  
be compatible with the IBM-3033 FORTRAN 77  
compilers.

```

MAIN PROGRAM KALMN2
  CARDIO
    LLHXYZ
    SIGXYZ
      MATRIX
        LINV2F
        VMULFF
        VMULFM
  INDAT
    TIMEUP
    PROMPT
    GETDAT
    DEDPDT
    DEFBR
    CRDAT
    BSADR
    CRDAT2
    NEWRAN
    IONRD
    ION
    IONRD
    EPHDAT
    CLOCK2
    CLOCK
    SATPOS
    ESTPOS
    ZANG
    RES
    SMOT
    TROP
    REL
    FSIG
    GDOP
    LINV3F
    KALFIL
    INKAL
    UDFACT
    LLHXYZ
    RGKAL
    UPDATE
    DPKAL
    UPDATE
    CONSTR
    UPDATE
    XYZLLH
    PRNSOL
    COVEVL

BLOCK DATA

```

## APPENDIX G

### INPUT GUIDE FOR PROGRAM KALMN2

( by S. L. Meyerhoff, NSWC)

Var	Type	Description
<i>CARD ONE</i> <span style="float: right;"><i>Format (2F10.0,6I5)</i></span>		
(This card can be read format free)		
col 1 to 10 TSS	real	The GPS time-tag for data at start of solution (seconds)
col 11 to 20 TES	real	The GPS time-tag of last data point to use in solution (seconds)
col 21 to 25 (right justified) NPN	integer	The number of time lines between solutions
col 26 to 30 (right justified) NPB	integer	The number of solutions between solutions being printed
col 31 to 35 (right justified) ITRY	integer	The number of solutions printed covariance matrix prints
col 36 to 40 (right justified) NSAT	integer	The number of trackers to process in the solution (range 1 to 4)
col 41 to 45 (right justified) IGT	integer	= 1 if data source is standard 9-track format = 2 if data source is other
col 46 to 50 (right justified) ISP	integer	= 1 for satellite position from NAVIGATION DATA MESSAGE = 2 for satellite position from Celestial Earth Fixed Trajectory files
col 51 to 55 (right justified) ICLOCK	integer	= 0 clock corrections are from NAVIGATION DATA MESSAGE = 1 clock corrections are post fit data from cards
col 56 to 60 (right justified) IAGE	integer	= 1 make GDOP file otherwise no file is made
col 61 to 65 (right justified) IAGE	integer	= 1 solve for clock aging otherwise no file is made
<i>CARD TWO (Receiver Position)</i> <span style="float: right;"><i>Format (I10,7G10.0)</i></span>		
(This card can be read format free)		
col 10		

IFLAG	integer	= 0 for Cartesian coordinates = 1 for Geodetic coordinates
col 11 to 20 XLAT	real	latitude or X coordinates for position (degrees or kilometers)
col 21 to 30 YLOG	real	longitude or Y coordinate for position (degrees or kilometers)
col 31 to 40 ZHT	real	height or Z coordinate for position (kilometers)
col 41 to 50 TB	real	time bias for receiver clock (kilometers)
col 51 to 60 TD	real	time drift for receiver clock (kilometers/second)
col 61 to 70 TO	real	epoch for clock drift (given and solution) if negative, then first used time line is the epoch for the solution clock drift
col 71 to 80 AGE	real	aging for receiver clock (kilometers/second*second)
<i>CARD THREE (Reference Geoid) Format (2G10.0)</i> (This card can be read format free)		
col 1 to 10 AG	real	semi-major axis of the reference geoid (kilometers)
col 11 to 20 ROBL	real	obliquity of the reference geoid
<i>CARD FOUR (Sigmas for Position) Format (7G10.0)</i> (This card can be read format free)		
col 1 to 10 SIGLT	real	sigma of X or latitude coordinate (kilometer)
col 11 to 20 SIGLG	real	sigma of Y or longitude coordinate (kilometer)
col 21 to 30 SIGHT	real	sigma of Z or height coordinate (kilometers)
col 31 to 40 SIG(1)	real	sigma on refraction scaling constant
col 41 to 50 SIG(2)	real	sigma on receiver time bias (kilometer)
col 51 to 60 SIG(3)	real	sigma on receiver clock drift (kilometer/second)
col 61 to 70		



SIG(4)	real	sigma of velocity in X direction (kilometers/second)
--------	------	---

*CARD FIVE (Sigmas for Velocity) format (7G10.0)*  
(This card can be read format free)

col 1 to 10 SIG(5)	real	sigma of velocity in Y direction (kilometers/second)
-----------------------	------	---

col 11 to 20 SIG(6)	real	sigma of velocity in Z direction (kilometers/second)
------------------------	------	---

col 21 to 30 SIG(7)	real	sigma on receiver time bias (kilometers)
------------------------	------	---

col 31 to 40 SIG(8)	real	sigma on receiver clock drift (kilometers/second)
------------------------	------	--

col 41 to 50 SIG(9)	real	sigma not used
------------------------	------	----------------

*CARD SIX (Types of solutions to do) Format (16I5)*  
(This card cannot be read format free)

col 5 NSOL(1)	integer	= 1 for range position solution = 0 no
------------------	---------	---

col 10 NSOL(2)	integer	= 1 Height constraint on position = 0 constraint only if less than 4 satellites
-------------------	---------	---

col 15 NSOL(3)	integer	= 1 write position solution on file = 0 no solution saved
-------------------	---------	--

col 20 NSOL(4)	integer	= 1 to solve for refraction correction in position solution = 0 no
-------------------	---------	---

col 25 NSOL(5)	integer	= 1 to solve for refraction correction in velocity solution = 0 no
-------------------	---------	---

col 30 NSOL(6)	integer	= 1 to solve for clock drift from position solution = 0 no
-------------------	---------	--

col 35 NSOL(7)	integer	= 1 do a velocity solution (this has not been used before) = 0 no
-------------------	---------	--

col 40 NSOL(8)	integer	= 1 do a time update of covariance matrix = 0 no
-------------------	---------	--

col 50		
NSOL(10)	integer	= 1 for a constraint on velocity solution
		= 0 no

col 1 to 10		
K2	real	bias factor for variance on range data

col 11 to 20		
K4	real	bias factor for variance on Doppler data

```
col 5      integer      = 1 print position solution
IPRT(1)    (X,Y,Z)      = 0 do not print
```

```
col 10      integer      = 1 print solution sigmas and
IPRT(2)      clock terms
              = 0 do not print
```

```
col 15
IPRT(3)      integer      = 1 print data and time tags
               = 0 do not print
```

```
col 20
IPRT(4)      integer      = 1 residuals, range, trop,
               data sigma
               = 0 do not print
```

```
col 25
IPRT(5)      integer      = 1 print satellite position
               = 0 do not print
```

```
col 30
IPRT(6)      integer      = 1 residuals and all data
               corrections
               = 0 do not print
```

```
col 35
IPRT(7)      integer      = 1 print position in lat, long,
               and height
```

```
col 40
IPRT(8)      integer      = 1 print real time solutions from
9-track
```

*CARD NINE (weather Data, Elev. Cutoff) Format (4G10.0)*  
(This card can be read format free)

col 1 to 10      real      pressure in millibars

col 11 to 20	real	temperature in degrees Centigrade
--------------	------	-----------------------------------

col 21 to 30		
HD	real	relative humidity in percent
col 31 to 40		
EL	real	elevation angle cutoff (degrees)
<i>CARD TEN (Station Number)      Format (Free)</i>		
(This card can be read format free)		
col 1 to 10		
Q(1)	real	time propagation noise for X velocity (kilometers)
col 11 to 20		
Q(2)	real	time propagation noise for Y velocity (kilometers)
col 21 to 30		
Q(3)	real	time propagation noise for Z velocity (kilometers)
col 31 to 40		
Q(4)	real	time propagation noise for time drift
col 41 to 50		
SIGPS	real	sigma on position constraint
col 51 to 60		
SIGVL	real	sigma on velocity constraint
<i>CARD ELEVEN (Diagonal elements of state transition matrix)</i>		
(This card can be read format free)		
col 1 to 10		
PHI(1,1)	real	state transition matrix for parameter 1
col 11 to 20		
PHI(2,2)	real	state transition matrix for parameter 2
col 21 to 30		
PHI(3,3)	real	state transition matrix for parameter 3
col 31 to 40		
PHI(4,4)	real	state transition matrix for parameter 4
col 41 to 50		
PHI(5,5)	real	state transition matrix for parameter 5
col 51 to 60		
PHI(6,6)	real	state transition matrix for parameter 6
col 61 to 70		
PHI(7,7)	real	state transition matrix for parameter 7
<i>CARD TWELVE (Diagonal elements of state transition matrix)</i>		
(This card can be read format free)		
col 1 to 10		
PHI(8,8)	real	state transition matrix for parameter 8
col 11 to 20		

PHI(9,9)            real            state transition matrix for  
parameter 9

*CARD THIRTEEN (Height for position constraint)*  
(This card can be read format free)

col 1 to 10  
HT            real            Height above reference  
                                 ellipsoid to constrain  
                                 position solution to  
                                 (kilometer)

## APPENDIX H

### ABBREVIATIONS AND ACRONYMS

GPS	=	Global Positioning System
NPS	=	Naval Postgraduate School Monterey CA
DMA	=	Defense Mapping Agency
NOAA	=	National Oceanic and Atmospheric Administration
NSWC	=	Naval Surface Weapons Center
SV	=	Space Vehicle
SEP	=	Spherical Error Probability
P-code	=	Precision code
C/A-code	=	Coarse Acquisition code
WGS	=	World Geodetic System
PDOP	=	Position Dilution of Precision
HDOP	=	Horizontal Dilution of Precision
VDOP	=	Vertical Dilution of Precision
TDOP	=	Time Dilution of Precision
SEF	=	Standardized Exchange Format
CIO	=	Conventional International Origin
ARL	=	Applied Research Laboratories at the University of Texas at Austin
IBM	=	International Business Machines
CDC	=	Computer Data Corporation
m	=	meters
km	=	kilometers
s	=	second
Hz	=	Hertz
MHz	=	Megahertz

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